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Energy resilient urban form: a design perspective

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Abstract

The paper introduces a design perspective of making energy resilient urban form, an approach to promoting energy performance through changing urban physical form. Existing urban energy research is often limited to performance analysis based on a positive question such as: "how urban systems function in energy efficiency". The paper raises a normative question: "how urban form should be designed or changed to achieve better energy performance and system resiliency". A research framework is suggested, including 1) energy flows in Euclidean geometry, 2) Gibson and Lynch's perceptual environment, 3) material flows and embodied energy, and 4) cross-scale dynamics. A test case of urban district is conducted, which demonstrates how performance analysis and design are connected. The paper concludes that urban design can be conceived as a forward-looking modeling method for synthesizing complex and uncertain energy problems in cities. It contributes to the agenda of creating a "normal science of urban energy modeling".

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Keywords: urban energy; urban design; energy performance; resiliency; design for change

1. Introduction

The paper lays out a research method on urban energy systems design, focusing how their urban physical form should be structured and designed for enhancing energy performance. We have observed growing number of efforts and attempts to develop energy efficient cities. Serious research on measurement and evaluation of urban energy system performance are emerging [1]. However, the dimension of physical form and its design method at the urban and community level is still rare. The impact of energy problems on cities' physical structures and functions is still unknown to most researchers, practitioners and policy makers. Research methodology and analytical approaches applicable to understanding urban energy systems and its linkage to design are to be further developed. In other word,

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research on how energy flows in cities across different levels of urban physical form from buildings, street blocks, urban districts, communities, cities to region are largely unexplored, and their design strategies are needed for promoting high performance and energy resilient systems.

How does urban physical form structure energy flows in cities, and how patterns of energy flows can be mapped through locations, spatial patterns, urban physical configurations and their dynamic processes? To understand how urban energy systems function in space and time, there is a need to investigate not only the network per se, e.g. the power grid or energy and material recycle loop, but also the urban form behind the networks and connections that accommodates energy flows in cities.

There exist extensive research and evidences on how physical spatial configurations and their changes affect patterns of flows in related fields such as landscape ecology, focusing on ecological flows at the levels of landscape and region [2]. However, it is still unclear how those principles could be applied to energy flows in urban settings. Some urban ecologists have pointed out that the physical form of cities only affects human behavior indirectly and its relationship to social and ecological consequences appears complex, uncertain and mismatch in scale [3]. While some patterns of flows are physical and visible, many others are relational like social relationship, stochastic like water and species flows, or formless, like energy flows.

The method of measuring how energy flows perform on various urban forms or urban physical structures, and how we design for it will be central to this agenda. To see cities as urban systems provides a functional perspective, in which energy "transcends traditional or administrative system boundaries" [1]. The very first challenge of conducting urban energy research is to define the system boundaries of cities, in which the estimation of energy use varies according to different definition of boundaries and their corresponding spatial scales.

The paper advocates a new urban energy research to move a focus from systems performance to systems design for achieving energy resilient urban form. The *systems performance analysis* addresses how cities functions and perform, a positive question which involves energy flows across territories and scales over different temporal processes. The *systems design approach* deals with how new urban form is designed through promoting energy performance and system resiliency, a normative question and a forward-looking perspective which sees cities as inherently flow-driven spatial organizations, a form of urban metabolism.

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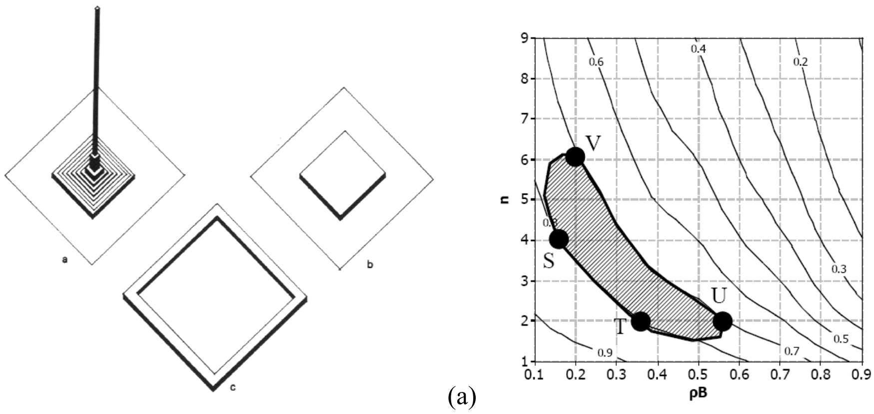
2. Four questions to define research dimensions of energy resilient urban form

What constitutes energy resilient urban form, and how do we design for it? The following organizational principles are suggested to outline a research framework of urban energy systems and their design: 1) *Euclidean urban geometry, 2) Gibson and Lynch's perceptual environment, 3) Material flows and embodied energy, and 4) Cross-scale dynamics*. Four questions are raised for responding to different dimensions or steps of operating urban energy research of this kind:

- 1. *Euclidean urban geometry*: What constitutes energy efficient urban form, and what urban forms perform better in energy efficiency?

The energy flow is a key driver behind the appearance and change of physical environment [4]. The energy performance of urban form is central to a relatively broad question of sustainable urban form [5]. However, energy is "formless" and its pattern is difficult to be visualized in cities. The linkage of energy and form is weakly connected. Martin and March raised a question "what makes the best use of land" by constructing the relationship between density, spatial typology and performance [6]. The following test case applies the principle of Fresnel diagram (Figure 1a) on how various urban typologies given the same density would potentially generate different patterns of energy flows, e.g. solar availability.

An experimental built form was conducted based on a fixed building density, in which the variable of building cover ratio ranges from 100% to 10% and their corresponding building heights varies from one to ten stories were applied to generate different building form from a flat pavilion to a point tower. The test case shows how the variation of building coverage and building height or the number of building story produces different typologies that would create different patterns of daylight exposure. The points V, U, S, T indicate the sky view factor ranging between 0.7 to 0.8. The denser of the built form is, the lower the daylight exposure will normally be (Figures 1b). The relationship among density, urban form typology and the energy consequence is clearly observable and their performance measure is essential to making better performance through urban design.



(a) (b)

Fig. 1. (a) Fresnel diagram [6]; (b) Variation of building typology to create patterns of daylight exposure (n: number of building stories; ρB: building coverage ratio)

- 2. *Gibson and Lynch's perceptual environment*: How do we measure energy flows in cities, in which their human effects are determined by individual positions and environmental perceptions?

The first proposition takes urban form as a Euclidean geometry. By measuring the Euclidean spatial attributes, such as density and parameters in typology, their corresponding energy performance can then be tested and correlated. Energy flows in cities produce thermal effect and define the degree of human comfort. How we measure patterns of energy flows that create impacts to human needs depends on individual positions in context and how human perceives the environmental. Cities are perceptual environment [7]. The urban space is seen as a continuous field [8], in which the human senses and experiences define and structure ecological effects of cities. The urban and natural world can be understood as agent-based complex systems or dynamic networks of many interacting agents in cities and ecosystems. The search for general principles underlying the internal organization of such systems often uses bottom-up simulation models such as cellular automata and agent-based model [9]. The viewpoint of individual agent, or users, and their responding behavioral patterns in environment is therefore crucial to urban energy research.

The *Sky view factor* is a simple tool that connects urban form, perceptual environment and performance. It measures the quantity of visible sky at a specific location, or the proportion of the sky that is visible from any given observer [10]. It is an indicator of urban climatology extensively tested in literature that has been found strongly correlated to both surface temperature pattern in local scale [11] and urban heat island effect in city or regional scale [10]. In the test case above, the measure of the sky opening refers to the amount daylight that can be received from the ground that would affect thermal comfort and solar availability (Figure 1b).

- 3. *Material flows and embodied energy*: How do we track energy and material flows over a heterogeneous urban physical structure, such as land uses, land covers, landscape mosaics, infrastructural and building surfaces that accommodate and embody energy flows that transcend territories or systems boundaries? How do we reconstruct a symbiotic relation, and then design for urban metabolism?

Urban environment is more than the geometry or the way of seeing. The material dimension of cities influences how patterns of energy flows are structured, organized and embodied. A city is like a reservoir of materials, and we should conduct a comprehensive urban metabolic study of material flows into and from the urban areas or cities to explore the issues of material efficiency, intensity, distribution and their recycle strategy [12]. Cities are seen as an urban metabolism [12] [13]. A symbiotic relationship could be developed through collaboration among different firms and industrial stakeholders to build industrial ecosystems [13].

An investigation of material stocks over an urban development process at the scale of urban district is needed, in which the results of the test case are to be further developed in future research of the next step (Figure 2a). By tracking the amount of materials consumed by the construction industry, the material flows and embodied energy are measured and their spatial distributions can be identified. Unlike industrial products, an urban system contains a comparatively long life and constant changes over time. The built environment is normally multi-functional, unique and contextual that causes local impact. The urban energy design research extends the system boundary from a single product of building components, a building system to broader-scale urban systems at a district level. A further life cycle assessment (LCA) can be conducted [15]. However, the degree of complexity would increase dramatically when the systems boundary is scaled up.

- 4. *Cross-scale dynamics*: How do we articulate multiple patterns of energy flows across different spatial scales from buildings, districts to cities, and what are their cross-scale dynamics? How do we then define the “focal scale” for design intervention to bridge the “finer scale” initiatives and to create the “coarser scale” effects?

The first three questions on geometric, perceptual and material dimensions are situated in a hierarchical structure from finer to broader scales of building, district and city, in which energy flows across levels and scales. The fourth question addresses their cross-scales relationship, in which the analytical framework depends on how we define the system boundary. The urban energy system resiliency can be defined as the capacity of an urban system to absorb disturbances or impacts from energy flows operating at the scales below, and to contribute positively and constructively for scales above, as well as the system’s ability to reorganize itself. The idea *panarchy* describes the structure of an entire multi-scale system, in which the patterns of flows in one scale are influenced by the patterns at the scales above and below [16]. More evidences of system dynamics are needed for understanding the properties of urban energy systems.

An interventional approach is taken in this paper when facing the scale dynamics: How do we choose a right spatial scale (and in right times with right decisions), or a “focal scale” as a framework to accommodate the below “finer scale” design initiatives, e.g. an energy zero building, and at the same time to create constructive impact to the above “coarser scale” system, e.g. an urban climate zone for the change? In the test case, a focal scale was defined based on a district-level urban block structure. By redesigning a current urban form structure (Figure 2a) and by maximize its “solar envelop” along the street front, the urban energy performance can be enhanced by 63.7% (Figure 2b) or 69.2% (Figure 3c) in total carbon reduction through adding the reduction of energy consumption and the increase of renewable energy gain through low energy urban design strategies [17].

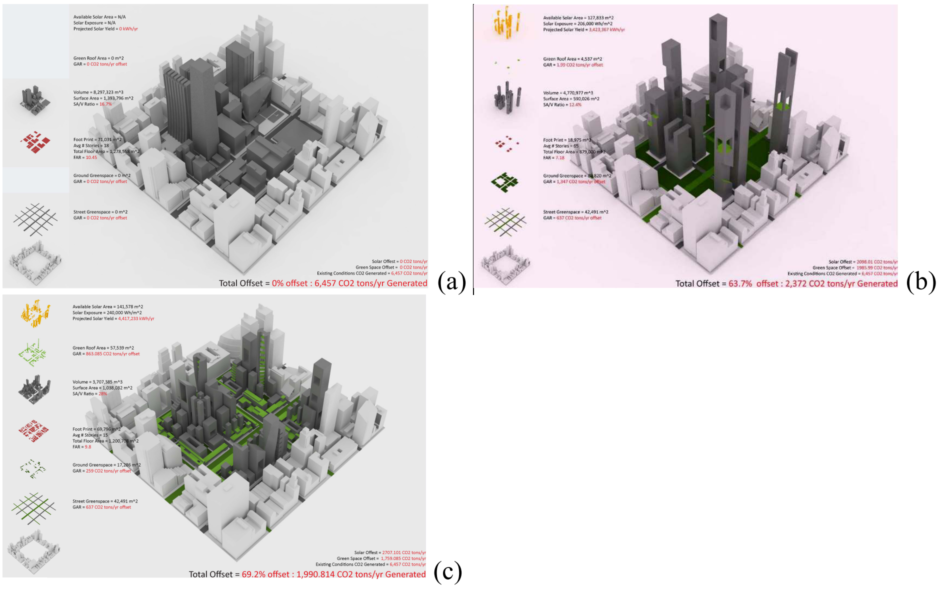


Fig. 2. A focal scale urban modeling for energy performance [17]: (a) existing; (b) 63.7% carbon reduction; (c) 69.2% carbon reduction

3. Conclusions

The organizational principles of designing energy resilient urban form are to be operated based on analyses of Euclidean urban geometry, perceptual environment, material flows and embodied energy, in which energy flows penetrate through them and are situated in complex cross-scale dynamics. However, the relationships among the four principles are not completely understood because they are neither hierarchical nor sequential. They are like dimensions and facets of design inquiries that allow urban designers to operate performance analysis and design for energy problems in cities.

How does energy performance enhancement inform urban design decision making to achieve outcomes of system resiliency? The paper advocates an interventional approach and sees urban design as a tool or instrument for making the change. It synthesizes complex factors and energy problems across spatial scales. New urban physical form and structure emerges from the promotion of urban energy functions. Finally, can urban design be turned into a variable of the performance-based urban modeling, and contribute to a "normal science of urban energy modeling" [18]? This will form a future direction for the research agenda of urban energy systems design.

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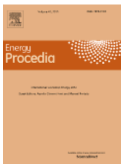

Biography

Perry Yang is Associate Professor at College of Architecture, the Georgia Institute of Technology, and co-directs the *Sino–U.S. Eco Urban Lab*. He is the Bayer Chair Professor at the UNEP- Tongji Institute of Environment for Sustainable Development. His work focuses on promoting ecological performance of cities through urban design.